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# SATELLITE MEASUREMENTS OF THE CHARGE COMPOSITION OF SOLAR COSMIC RAYS IN THE 6≤Z≤26 INTERVAL


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# SATELLITE MEASUREMENTS OF THE CHARGE COMPOSITION OF SOLAR COSMIC RAYS IN THE $6 \leq Z \leq 26$ INTERVAL

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ABSTRACT

We report measurements of the charge composition of solar cosmic rays during two flares occurring in April and September, 1971. The results were derived from a solid state dE/dx vs. E telescope which was part of the Goddard Cosmic Ray Experiment on the IMP VI spacecraft. Our data suggest that the helium to medium ratio may be varying from one flare to the next. We compare our abundance ratios (normalized to oxygen) with measurements of other investigators and find a number of significant disagreements. In particular, our data do not exhibit any systematic enhancement of heavy nuclei with respect to the spectroscopic abundances such as reported by Mogro-Campero and Simpson (1972 a, b). Finally, we compare our results with the spectroscopically determined coronal and photospheric values, and again we find several important differences between the two sets of data.

# SATELLITE MEASUREMENTS OF THE CHARGE COMPOSITION OF SOLAR COSMIC RAYS IN THE $6 \leq Z \leq 26$ INTERVAL

## INTRODUCTION

Until recently measurement of the composition of energetic solar flare particles has been confined to short-duration exposures of rocket-borne emulsions. This pioneering work has been done by Fichtel and co-workers at the Goddard Space Flight Center (Bertsch, et al., 1969, 1972; Biswas and Fichtel, 1965; Biswas et al., 1963, 1966; Durgaprasad et al., 1968; Fichtel and Guss, 1961). They have studied approximately eight major solar particle events over the past ten years. From this work a reasonably consistent picture emerged wherein the relative abundances of elements having the same charge to mass ratio remained constant from flare to flare and also as a function of energy. This behavior suggested that the abundances of energetic flare particles ($\gtrsim$ 10 MeV/nuc) did, in fact, reflect the composition of the solar atmosphere where they were produced. Further, it was found that there was general agreement between the relative abundances of solar flare particles in the charge range Z = 6 - 26 and the spectroscopically determined abundances in the solar atmosphere. One important consequence of this work was that the helium abundance in the corona, which could not be measured spectroscopically, could be determined using the solar cosmic ray abundances.

Recently, satellite measurements of the charge composition of solar flare nuclei have become available for the first time. They include the University of Chicago results from the OGO-V spacecraft (Mogro-Campero and Simpson, 1972a, b) and our own measurements (von Rosenvinge et al.,

1971) using a detector on board the IMP VI spacecraft. We will report on composition measurements made during two large events (April 6, 1971 and September 1, 1971). We will compare our results with the emulsion work and other measurements, and it will be seen that a number of important differences exist. We will examine the time and energy dependence of certain elemental abundance ratios. Finally, we will compare our results with the spectroscopically determined photospheric and coronal abundances.

## DESCRIPTION OF THE EXPERIMENT

The Goddard cosmic ray experiment on the IMP VI spacecraft consists of several different charged particle telescopes. In this paper we report on the results from one of these, a solid state dE/dx vs E telescope referred to as the low energy detector (LED). This telescope is shown in Figure 1a. The front element is a thin 150 μ (.035 g/cm$^2$) silicon surface barrier solid state detector. Its purpose is to measure the particle's rate of energy loss dE/dx. The second element E is a 3000 μ (.705 g/cm$^2$) lithium drifted device used to measure the particle's total energy. The plastic scintillator anti-coincidence cup C serves the dual functions of first, defining the acceptance cone of the telescope and, second, rejecting those particles that penetrate through the E element. The thicknesses of the dE/dx and E elements define, respectively, the lower and upper energy limits on the response of the LED. For dE/dx vs E analysis the instrument covers the range 4 - 23 MeV nucleon$^{-1}$ for protons and alphas and successively higher intervals for higher charges. Particles which come to rest in the dE/dx element are also identified and analyzed, which allows an extension of the response of the instrument to lower energies. Charge resolution is, however, poor in this region.

One difficulty associated with solar cosmic ray composition measurements is the fact that the higher charges comprise only a very small fraction of the total flux of particles incident on the detector. Typically, there will be on the order of one heavy nucleus for every 1000 protons entering the detector. The spacecraft has a fixed data transmission rate which permits us to analyze only 1.6 particles per second. In general the rate of particles incident upon the telescope is much larger than this during a flare so that, in effect, we are sampling only a small fraction of the incoming flux. If only one in a thousand is a heavy nucleus then we would measure only one heavy nucleus every 1600 seconds. During the course of a flare we would then expect to sample a maximum of only 50-100 heavy nuclei. To improve this situation we have included in the experiment electronics a "Cancro priority system" (Cancro, 1969) to preferentially select for analysis the higher charges in the incoming flux of particles. The basis upon which the selection is made is shown in Figure 1b. The energy loss in the dE/dx element vs. the energy loss in the E element is plotted for both protons and alpha particles. The dashed line defines the boundary between the so-called low gain and high gain regions. In terms of the experiment electronics this dashed line is formed by simply taking a linear sum of the dE/dx and E signals and determining whether this is greater than a suitably chosen threshold value. If this threshold is exceeded the event is tagged as a heavy particle and in general it will be given priority over the more abundant protons and alphas for analysis and readout. During the

September 1, 1971 event we accumulated approximately 5000 nuclei with $Z \geq 3$. In the absence of the priority system this number would have been close to 50. Separate independent measurement of counting rates allows the normalization of pulse height data to obtain absolute spectra. The $3 \leq Z \leq 26$ interval, however, is a single discrete group within the priority system. One can therefore obtain abundance ratios in this interval directly from the pulse height data without using the rates normalization procedure and essentially neglecting the presence of the priority system.

EXPERIMENTAL RESULTS

Data Analysis

The results to be presented in this paper are all derived from two parameter dE/dx vs. E data in which the analysis is straightforward. We show in Figs. 2a and b two dimensional pulse height distributions with the dE/dx and E detectors, respectively, on the vertical and horizontal axes. In Fig. 2a the first 128 channels are shown in full resolution. This is the low gain mode of operation wherein protons and alphas are excluded. It is apparent that the medium nuclei are well resolved. The light element region below the carbon line is seen to be quite background free with the exception of a small region near the vertical axis. This background "clump" is probably caused by the pile-up of low energy alpha particles and is excluded from the analysis. Fig. 2b shows the full 512 channels of pulse height data compressed by a factor of four. The presence of the higher charges is now evident with the light heavy elements Ne, Mg, Si, S well resolved. There is also a clear iron line present containing approximately 35 particles. The curves drawn through each of the distributions are derived from the well known range energy relations and are normalized to the data at only one point, the end of the oxygen line. The excellent fit of these curves to the data over such a wide range in charge and energy gives us a very high degree of confidence in our knowledge of the detector response.

The charge resolution of the instrument is shown in a one dimensional representation in Fig. 3. This plot was generated using the data shown in Figs. 2a and b. For each point in Figs. 2a and b the distance to the nearest theoretical curve was calculated. Fig. 3 is then the distribution of events as a function of distance away from the appropriate curve. It is evident that there is no difficulty whatsoever in resolving the elements C, N, O, Ne, Mg, Si, and S. There is also a distinct peak in the vicinity of iron. Due to the close spacing of the particle lines in this region we have been unable to separate iron from its nearest neighbors. In the following we therefore adopt a procedure used by many others, namely to quote an "iron group" abundance which covers the range from Cr to Ni. The above mentioned elements are the only ones for which we quote abundance ratios. We emphasize that for all these elements (or groups of elements) clearly resolved peaks are present. Furthermore, we suggest that the kind of representation shown in Fig. 3 is the best way to compare and evaluate the various experimental techniques that have been used to measure the charge composition of solar cosmic rays.

## Relative Abundances of $Z \geq 3$ Nuclei

We now turn our attention to the $Z \geq 3$ region and examine the detailed charge composition. In Fig. 4a the carbon and oxygen spectra are plotted as a function of energy nucleon$^{-1}$ for data taken during the September 1, 1971 event. It is clear that a power law is not a particularly good fit to the spectra. The hardening at lower energies reflects the propagational difficulties encountered by the low energy particles due to the fact that this was an event most probably occurring 30° behind the west limb of the sun (Van Hollebeke et al., 1972). In Fig. 4b we show the carbon-to-oxygen ratio as a function of energy nucleon$^{-1}$. The data are consistent with no variation of this ratio as a function of energy.

Fig. 5 shows the individual spectra for neon, magnesium, and silicon. The dashed line indicates the oxygen spectrum. It is clear that no dramatic departures from oxygen in the spectral shapes of these elements are present. Poor statistics prevent us at this time from plotting spectra for any other of the observed heavy elements.

The detailed charge composition for $6 \le Z \le 26$ is shown in Table 1. We have also shown for purposes of comparison the rocket-emulsion data of Bertsch et al. (1972), the satellite data of Mogro-Campero and Simpson (1972b), and the rocket-borne plastic detector data of Sullivan et al. (1972). We have shaded the boxes for those elements where we feel that a significant disagreement exists. Our data from the April 6 event are corrected for the variability of the detector threshold with energy. This procedure was necessary due to the relatively low fluxes and resultant poor statistics during this event. We observed many more heavy nuclei, however, during the September 1 event and consequently were able to derive abundance ratios for each element between oxygen and iron using identical energy nucleon$^{-1}$ windows (13.5-47 MeV nucleon$^{-1}$). The 13.5 MeV nucleon$^{-1}$ value is the lower threshold for iron and the 47 MeV nucleon$^{-1}$ value is the upper threshold for oxygen. The helium abundance quoted in Table 1 covers the interval 8.5-23 MeV nucleon$^{-1}$ where the lower limit is that for oxygen and the upper limit is that for helium. The upper energy limits for carbon and nitrogen are only slightly different from 47 MeV/nucleon. The measurements of other investigators shown in the table are not taken in exactly the same energy nucleon$^{-1}$ interval but the differences are small enough so that no significant spectral effects are expected.

There is one important difference between the data of Sullivan et al. (1972) and the rest of the data shown in Table 1. At the time of writing the authors had no reliable oxygen abundance measurement, and we have normalized their data to our September 1 silicon-to-oxygen ratio (.107 $\pm$ .011). It should be kept in mind, however, that the relationship between the two sets of data could be drastically changed if they eventually derive an oxygen abundance which differs significantly from ours. Furthermore, it must be remembered that in using this normalization it is valid to compare the results of Sullivan et al. only with our results. A comparison of the Sullivan abundances shown in Table 1 with either the Bertsch et al. (1972) or the Mogro-Campero and Simpson (1972b) results in the table would be totally fallacious since our silicon-to-oxygen ratio differs markedly from theirs. For this reason we will first compare our results with those of Bertsch et al. and Mogro-Campero and Simpson and then separately compare ours with those of Sullivan et al.

Turning now to an element by element discussion of Table 1 we begin with the helium measurements. These will be mentioned only briefly here since it is our intention to present a full discussion of the energy and time variations of the solar helium abundance in a later paper. We note that our value for the September 1 event differs by more than a factor of two from Fichtel's long-term average over many events. Our April 6 value lies in between and probably is significantly different from both of these results. These data then suggest that the variability of the helium abundance from one event to the next may be larger than the 20-30% upper limit indicated by the earlier rocket-emulsion data. Other investigators (Armstrong and Krimigis 1971; Armstrong et al. 1972; Beedle et al. 1971; Van Allen et al. 1971) have reported a variable He to CNO ratio at lower energies (~ 0.5 MeV nucleon$^{-1}$). This, however, is the first measurement which directly conflicts with the rocket emulsion work of Fichtel and co-workers in a comparable energy range.

In the light element region (Li, Be, B) the only values quoted are upper limits. We have, during the September 1 event, been able to reduce substantially the upper limits reported earlier by Bertsch et al. (1972). In the C-N-O region all measurements are in reasonably good agreement. The Mogro-Campero and Simpson (1972b) results for nitrogen are a factor of two above our September 1 value but the errors are large enough so that the values could be consistent. For neon the various values agree within errors. In the case of magnesium and silicon we again encounter disagreement. Our magnesium and silicon values are both approximately three times larger than those of Bertsch et al. (1972). For magnesium, Mogro-Campero and Simpson are in agreement with us, but for silicon they are more than a factor of five higher than our values. In the case of sulfur we agree with Bertsch et al. (1972) but are a factor of five below the University of Chicago result. Their error is, however, large enough so that the discrepancy may not be real. Turning to argon, we find that our upper limit is a factor of twenty below the value of Mogro-Campero and Simpson.

Again, however, their error is very large. The situation for calcium is very similar, with our upper limit a factor of ten below the University of Chicago value.

Finally, for the iron group elements our two measurements differ from each other by a factor of six. The error in the April 6 measurement is, however, large enough so that the results could be consistent with each other. Our September 1 value (the more accurate of the two) lies within the range reported by Bertsch _et al_. All of these values lie well below the iron abundance given by Mogro-Campero and Simpson. The University of Chicago value quoted in Table 1 is, however, an average over many flares in the 1968-1971 period, and these authors claim that their data show a large variability in the iron abundance from one flare to the next (Mogro-Campero and Simpson 1972b). In the two cases where they have measured the iron abundance during the same flare as either ourselves or Bertsch _et al_. (1972) they report at least qualitative agreement between the various measurements. It should be pointed out, however, that their evidence for the variability of the iron abundance comes from data taken at approximately 5 MeV nucleon$^{-1}$ where the situation may be entirely different than at the higher energies where the other measurements have been made. In particular at 5 MeV/nucleon$^{-1}$ the equilibrium charge of an iron nucleus travelling through matter is +21 and is strongly energy dependent, whereas at higher energies ($\gtrsim$ 30 MeV nucleon$^{-1}$) the nucleus becomes fully stripped. One might therefore expect to see more pronounced propagational effects in the iron abundance at lower energies where the effective charge-to-mass ratio of iron differs significantly from that of the lower Z elements.

Mogro-Campero and Simpson (1972a, b) report a systematic enhancement of the abundance of heavy nuclei ($10 \leq Z \leq 26$) over the solar spectroscopic abundances. Their enhancement appears to be increasing with charge and is approximately a factor of twenty by the time iron is reached. One should note that the errors in their sulfur, argon and calcium values are large enough to be consistent with no enhancement at all. One should further keep in mind that the uncertainties in the spectroscopic values are generally at least a factor of two. Their case for enhancement then rests mainly on three elements, magnesium, silicon and iron. With the exception of magnesium all other values for these nuclei measured by both Bertsch et al. and ourselves are consistently below the Mogro-Campero and Simpson results. We, therefore, find no evidence for the systematic enhancement of heavy nuclei reported by Mogro-Campero and Simpson (1972 a, b).

Finally, we compare separately our results with the rocket-borne plastic detector results of Sullivan et al. (1972; see also Price and Sullivan 1971). As mentioned earlier, we have adopted this procedure since their data are normalized to silicon whereas the rest are normalized to oxygen. The Sullivan et al. (1972) results are derived predominantly from the January 25, 1971 solar flare. With the possible exception of iron, our abundances and theirs are in agreement within errors. They have, however, determined a preliminary value for the iron abundance in the September 1, 1971 event which is more than a factor of two below the January 25 value (Sullivan, private communication). It is therefore unlikely that any disagreement exists.

In Fig. 6 we compare our solar cosmic-ray abundances discussed earlier with the spectroscopically determined coronal and photospheric abundances. In addition to the earlier normalization used by us (oxygen ≡ 1) we show the usual astrophysical normalization of $\log_{10}$ (hydrogen abundance) ≡ 12.0. The spectroscopic values were taken from the survey done by Bertsch _et al_. (1972). In general the range of spectroscopic values given for each element reflects the range in recent published values combined with the reported uncertainties in these values. The range given for iron differs slightly from the value of Bertsch _et al_. (1972) as a result of recent revisions of the oscillator strengths for iron (e.g. Garz and Kock 1969; Whaling, King, and Martinez-Garcia 1969; Bridges and Wiese 1970; Klose 1971). The question of whether or not local thermodynamic equilibrium can be assumed and whether, in fact, there is any real difference between the photospheric and coronal abundances remains a lively one. We have made no assumptions ourselves but have followed the procedure of Bertsch _et al_. (1972) and simply made the error bars large enough to include all of the recent values.

A further question arises, namely, whether or not the elemental abundances in active regions may be different from the ambient photospheric and/or coronal abundances. For example, the work of Chavalier and Lambert (1970) has suggested that the calcium abundance is enhanced by a least a factor of two in coronal condensations. This then casts further doubt on the validity of comparing the solar cosmic ray abundances with the spectroscopically determined ambient values.

Referring to Fig. 6 we first note that in the medium element region our values are in relatively good agreement with the spectroscopic values with the possible exception of coronal carbon.

Our solar cosmic ray value for neon agrees well with the coronal measurement. Because of its high first excitation potential, however, no spectroscopic measurement exists of the photospheric neon abundance. For both magnesium and silicon we find significant differences between our measurements and the spectroscopic values. Our magnesium abundance is 4-7 times higher than the photospheric value, and our silicon is 2 to 4 times higher than the photospheric value. The disagreement with the coronal values is probably not as large. For sulfur we have good agreement. In the case of argon, as with neon, no photospheric value exists. Our upper limit, however, lies a factor of 3 to 5 below the coronal value. Our calcium upper limit is well above the coronal and photospheric ranges so that no disagreement exists. The value we quote for iron really represents the iron group, Cr-Ni. There is, however, good reason to believe that iron dominates the iron group. We therefore have compared our iron group measurement with the coronal and photospheric iron abundances and find no disagreement.

## Summary and Conclusions

We have reported measurements of the relative abundances of solar cosmic rays ranging from helium to iron nuclei. A number of differences have arisen between ourselves and other similar measurements and between ourselves and the spectroscopic measurements. The individual abundance ratios that we determine in the $3 \leq Z \leq 26$ interval are in general in agreement with the spectroscopic values with three significant exceptions. Our magnesium and silicon measurements are higher and our argon upper limit is lower by substantial amounts than the spectroscopic values. We find no evidence, however, for the systematic enhancement of heavy

B

nuclei in solar cosmic rays relative to the photospheric abundances that was reported by Mogro-Campero and Simpson (1972 a, b). On the question of the variability of the iron abundance in solar cosmic rays our data are inconclusive. Our iron values differ by a factor of 5-6 between the April 6 and September 1 events. The errors are large enough, however, so that the difference could be statistical.

In conclusion, it appears that as more measurements of the solar cosmic-ray abundances have become available more and more differences have appeared between the measurements themselves and between the solar cosmic ray and spectroscopic abundances. Furthermore, our own data and other measurements at lower energies suggest that there may be a variation in the helium abundance from flare to flare. It therefore appears that we may well have to discard the simplistic view that solar cosmic rays are an unbiased sample of a uniform solar atmospheric composition. The study of solar cosmic ray composition might then be expected to become a means of learning more about the flare acceleration process and the homogeneity of the solar atmosphere.

## FIGURE CAPTIONS

Figure 1 a) Diagram of the IMP-VI Low Energy Detector
b) Response curves showing the boundary (dashed line) between the high and low gain regions. The boundary also defines the transition point between the low Z and high Z event types within the detector priority system.

Figure 2a Two dimensional dE/dx vs. E pulse height analysis data in the low gain mode of the LED. Only the first 128 channels are shown.

2b dE/dx vs. E pulse height data with all 512 channels plotted. Solid curves are calculated from range-energy relationships.

Figure 3 Charge histogram for the September 1, 1971 event. In regions II-IV the vertical scale has been expanded by a factor of two. In region II the horizontal scale is compressed by two; in region III it is compressed by four; in region IV it is compressed by sixteen. The energy interval for each charge is approximately 13.5-47 MeV nucleon$^{-1}$. The abundance ratios reflected here are not exact due to small differences in the energy intervals for each charge.

Figure 4a Carbon and oxygen spectra during the September 1, 1971 event as a function of energy nucleon$^{-1}$.

4b Carbon to oxygen ratio during the September 1, 1971 event as a function of energy nucleon$^{-1}$.

Figure 5 Neon, magnesium and silicon spectra as a function of energy nucleon$^{-1}$ during the September 1, 1971 event.

Figure 6 A comparison of the solar cosmic ray abundance measurements to the spectroscopic values for the photosphere and corona. The scale on the left is normalized to oxygen = 1 and the scale on the right is normalized to $\log_{10}$ (hydrogen) = 12.

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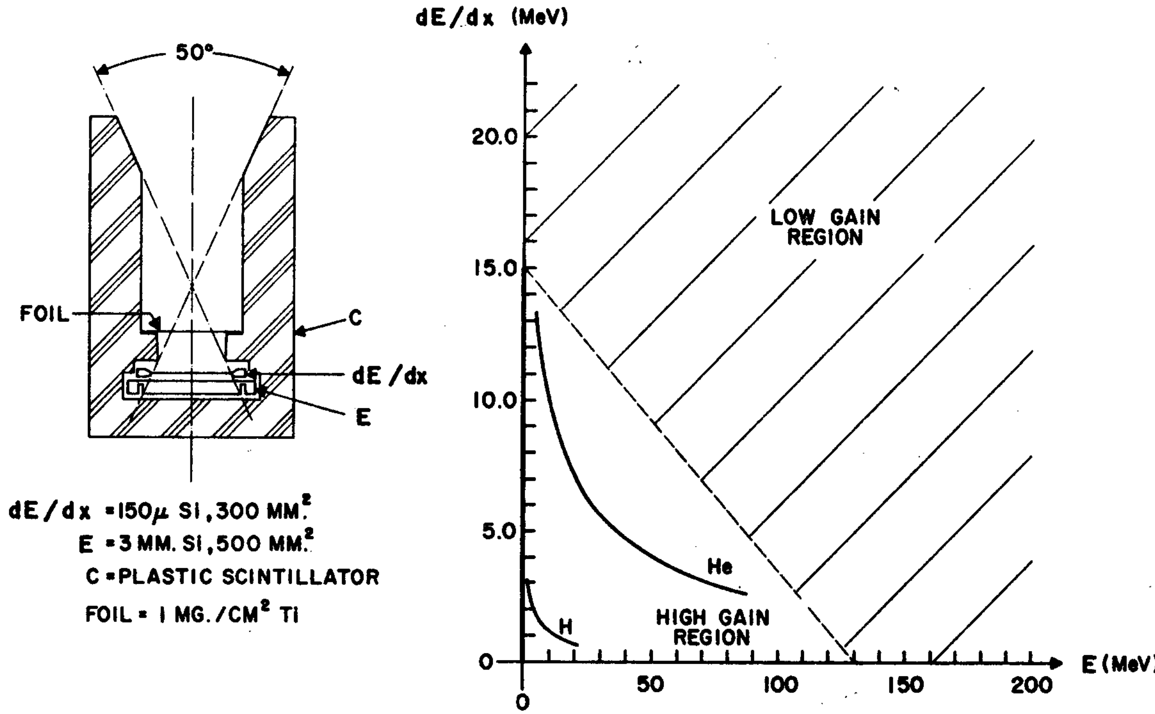
| | PRESENT WORK | | BERTSCH et. al. | MOGRO-CAMPERO AND SIMPSON | SULLIVAN, et. al. |
|---|---|---|---|---|---|
| | 6 APR., 1971 | 1 SEPT., 1971 | | | |
| He | 68 ± 14 | 42.0 ± 2.5 | 101 ± 10 | —— | —— |
| Li | —— | < .003 | —— | —— | —— |
| Be | —— | < .003 | < .02 | —— | —— |
| B | —— | < .008 | < .02 | —— | —— |
| C | .34 ± .08 | .49 ± .03 | .56 ± .06 | .42 ± .13 | —— |
| N | .15 ± .05 | .116 ± .011 | $.19^{+.03}_{-.07}$ | .23 ± .10 | —— |
| O | 1.0 | 1.0 | 1.0 | 1.0 | —— |
| F | —— | <.006 | —— | —— | —— |
| Ne | .11 ± .05 | .127 ± .011 | .16 ± .03 | .20 ± .10 | ~.11 |
| Mg | .20 ± .08 | .182 ± .014 | .056 ± .014 | .22 ± .11 | .13 ± .03 |
| Si | .11 ± .06 | .107 ± .011 | .028 ± .010 | .58 ± .21 | ≡.107 |
| S | —— | .025 ± .005 | .021 ± .007 | .13 ± .09 | .016 ± .007 |
| A | —— | <.004 | < .017 | .08 ± .07 | <.004 |
| Ca | —— | <.011 | <.010 | .10 ± .09 | .009 ± .006 |
| Cr-Ni | .17 ± .08 | .028 ± .005 | .03 – .06 | .79 ± .29 | .11 ± .03 |

TABLE 1




IMP-VI LED

FIGURE 1

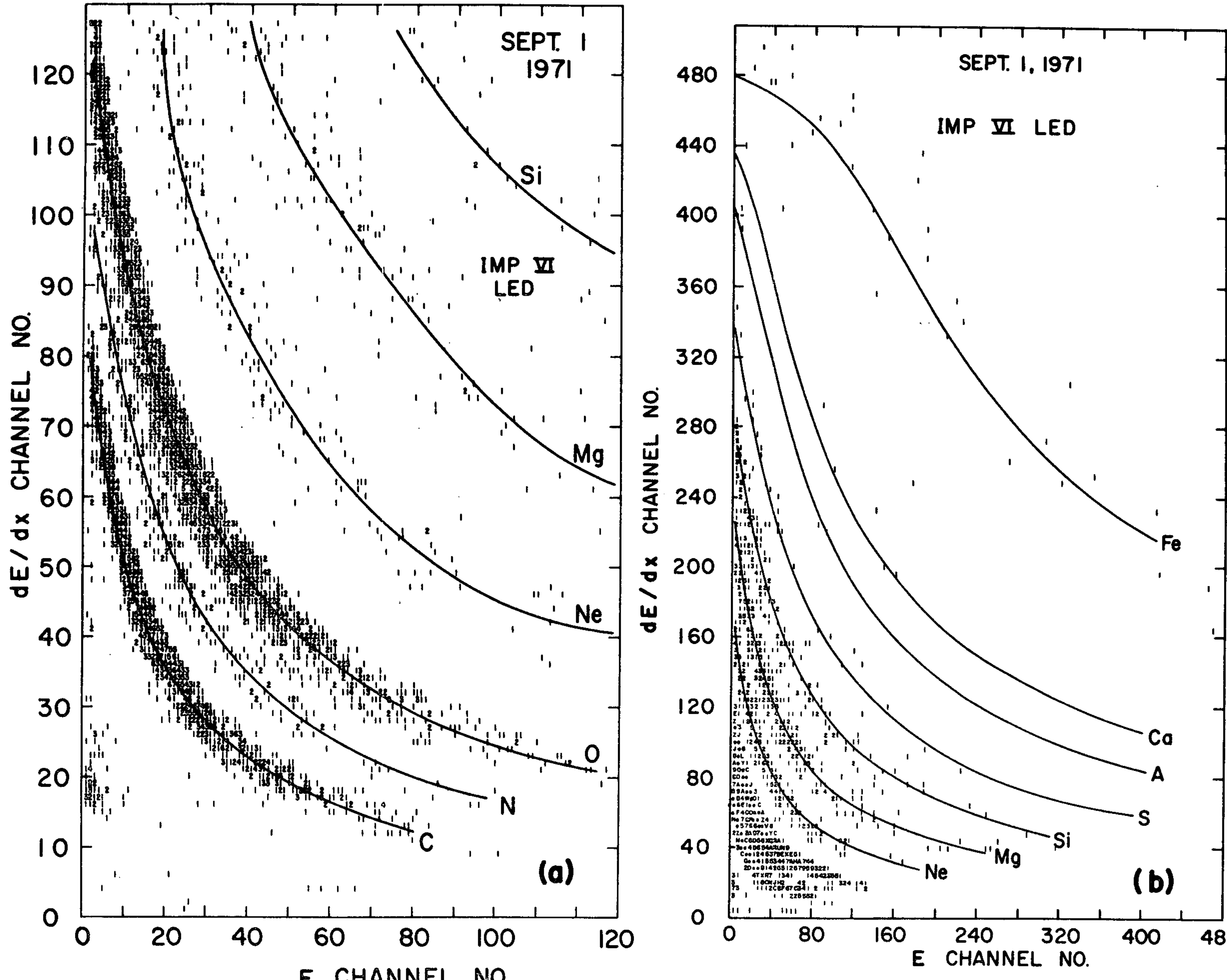

SEPT. 1 1971
IMP VI LED
Si
Mg
Ne
O
N
C
(a)
dE/dx CHANNEL NO.
E CHANNEL NO.
SEPT. 1, 1971
IMP VI LED
Fe
Ca
A
S
Si
Mg
Ne
(b)
dE/dx CHANNEL NO.
E CHANNEL NO.

FIGURE 2

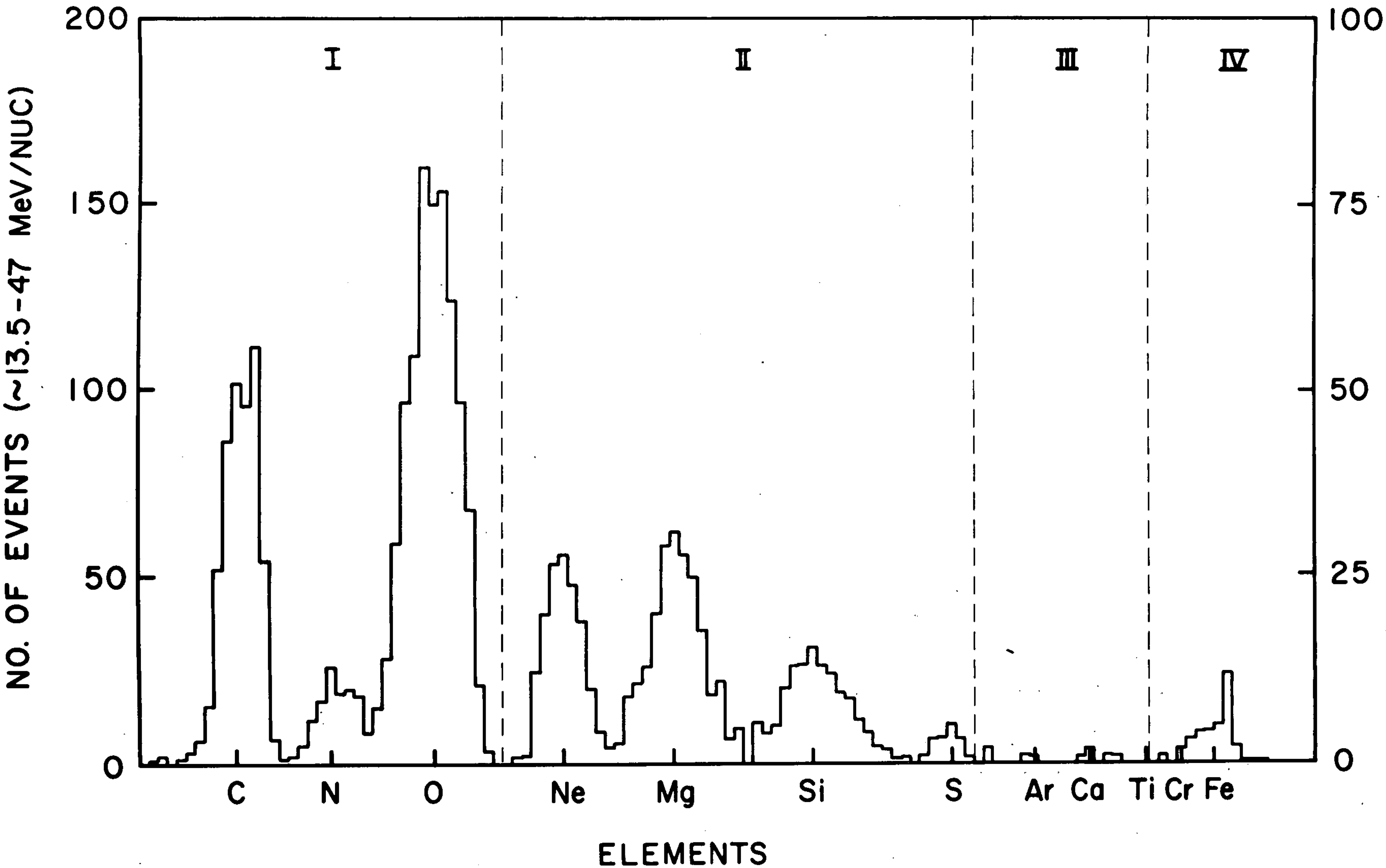
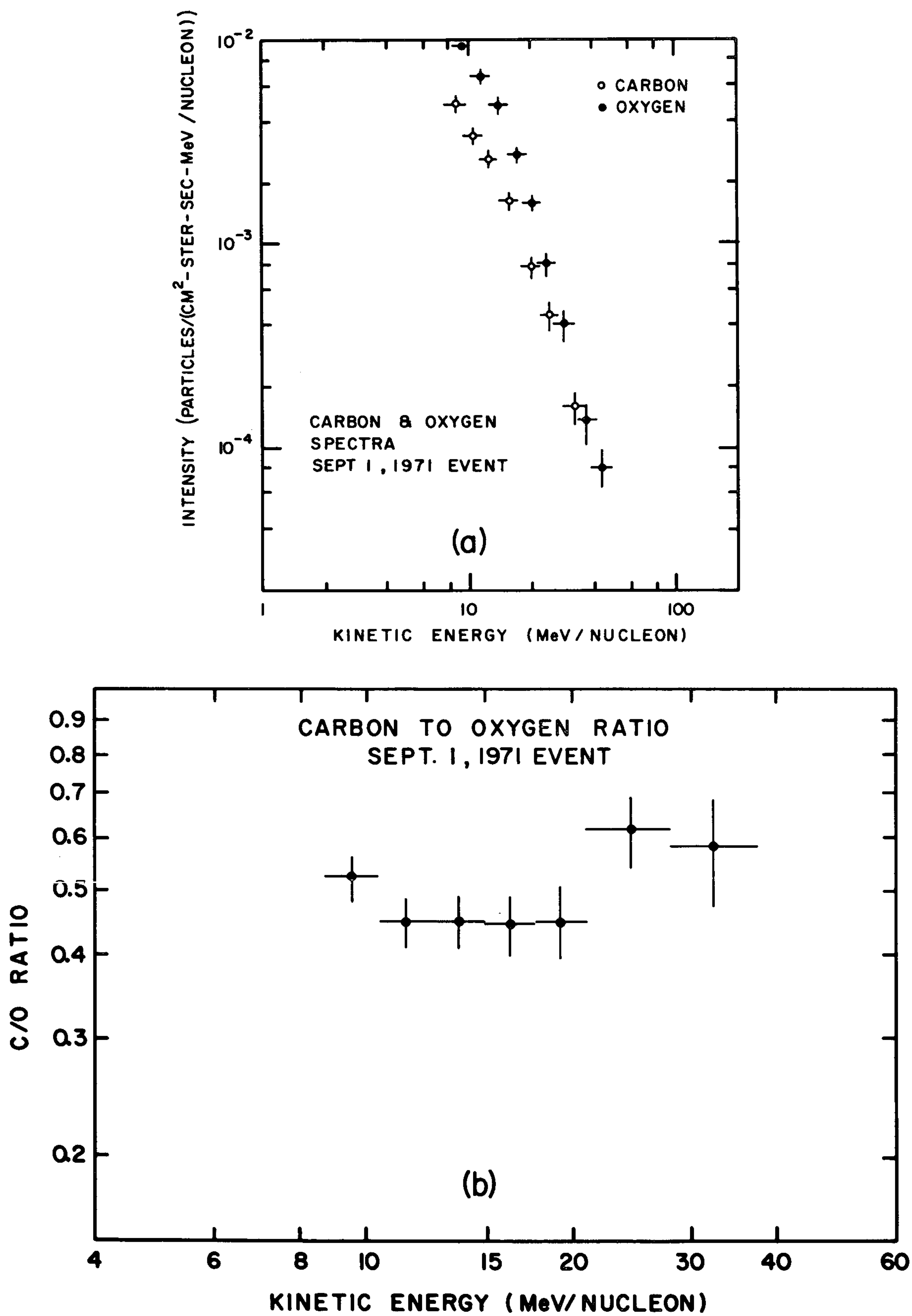
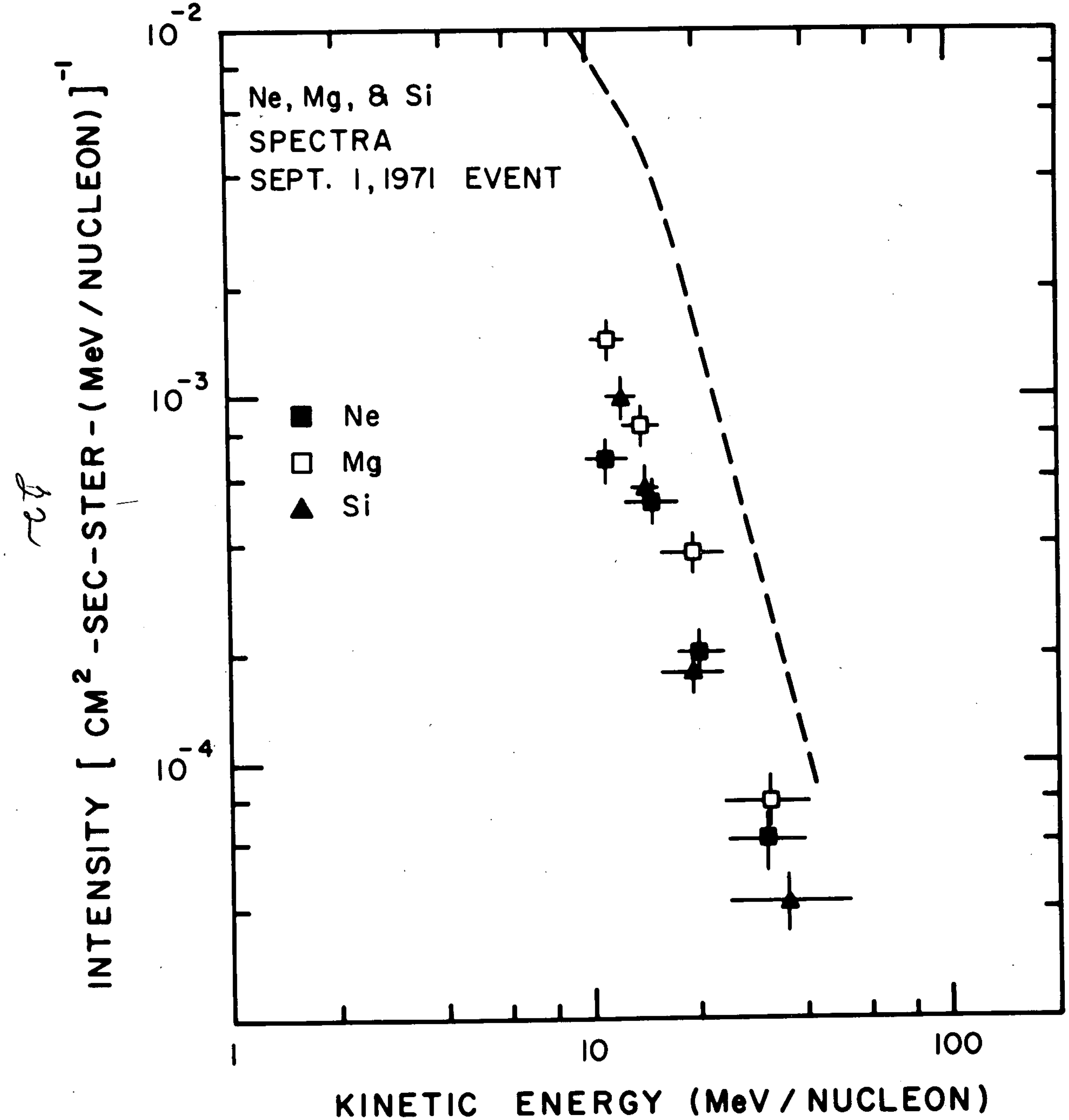

NO. OF EVENTS (~13.5-47 MeV/NUC)
200
150
100
50
0
100
75
50
25
0
I
II
III
IV
C
N
O
Ne
Mg
Si
S
Ar
Ca
Ti
Cr
Fe
ELEMENTS

FIGURE 3



INTENSITY (PARTICLES/(CM$^2$-STER-SEC-MeV / NUCLEON))
$10^{-2}$
$10^{-3}$
$10^{-4}$
o CARBON
• OXYGEN
CARBON & OXYGEN
SPECTRA
SEPT 1, 1971 EVENT
(a)
1
10
100
KINETIC ENERGY (MeV / NUCLEON)
CARBON TO OXYGEN RATIO
SEPT. 1, 1971 EVENT
C/O RATIO
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
(b)
4
6
8
10
15
20
30
40
60
KINETIC ENERGY (MeV/NUCLEON)


FIGURE 4



Ne, Mg, & Si
SPECTRA
SEPT. 1, 1971 EVENT
Ne
Mg
Si
$10^{-2}$
$10^{-3}$
$10^{-4}$
1
10
100
INTENSITY [ $CM^2$ -SEC-STER-(MeV/NUCLEON) $]^{-1}$
KINETIC ENERGY (MeV/NUCLEON)


FIGURE 5

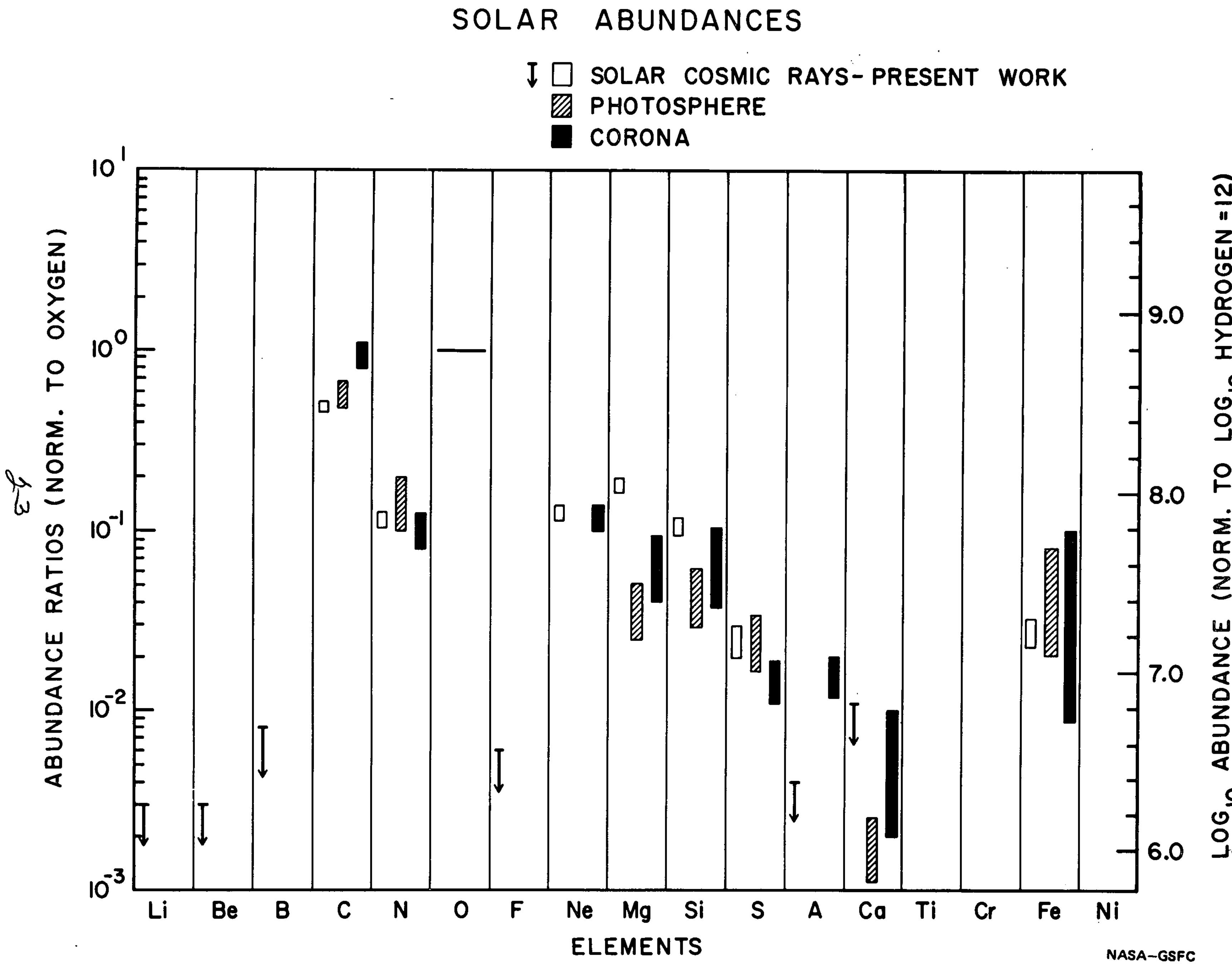

SOLAR ABUNDANCES
SOLAR COSMIC RAYS- PRESENT WORK
PHOTOSPHERE
CORONA
ABUNDANCE RATIOS (NORM. TO OXYGEN)
LOG10 ABUNDANCE (NORM. TO LOG10 HYDROGEN = 12)
10^1
10^0
10^-1
10^-2
10^-3
9.0
8.0
7.0
6.0
Li Be B C N O F Ne Mg Si S A Ca Ti Cr Fe Ni
ELEMENTS
NASA-GSFC

FIGURE 6